Characterization and Modeling of the Philippine Archipelago Dynamics Using the ROMS 4DVAR Data Assimilation System

Hernan G. Arango
Institute of Marine and Coastal Sciences, Rutgers University
71 Dudley Road, New Brunswick, NJ 08901-8521, USA
phone: (732) 932-6555 x266 fax: (732) 932-6520 email: arango@marine.rutgers.edu

Enrique Curchitser
Institute of Marine and Coastal Sciences, Rutgers University
71 Dudley Road, New Brunswick, NJ 08901-8521, USA
phone: (732) 932-7889 fax: (732) 932-8578 email: enrique@marine.rutgers.edu

Julia C. Levin
Institute of Marine and Coastal Sciences, Rutgers University
71 Dudley Road, New Brunswick, NJ 08901-8521, USA
phone: (732) 932-6555 x264 fax: (732) 932-6520 email: julia@marine.rutgers.edu

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LONG-TERM GOAL

The long-term goal of this project is to improve our capability to predict the inherent spatial and temporal variability near the Philippine Straits, and thus contribute to the development of reliable prediction systems.

OBJECTIVES

The primary focus is to provide a comprehensive understanding of the remote and local factors that control the meso- and submesoscale features in and around the Philippine Archipelago Straits. The main objectives are:

- to explore the effects on the Philippine Straits of remote forcing from the equatorial waveguides, throughflows, and adjacent seas mesoscale dynamics;
- to estimate the effects of local winds in generating meso- and submesoscale variability;
- to quantify the role of barotropic tidal forcing in promoting side wall eddies and internal tides;
- to study the role of abrupt changes in bathymetry in generating submesoscale variability; and
- to investigate the impact of variational data assimilation on the simulation and predictability of the meso- and submesoscale circulation features.

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14. ABSTRACT
The long-term goal of this project is to improve our capability to predict the inherent spatial and temporal variability near the Philippine Straits, and thus contribute to the development of reliable prediction systems.

15. SUBJECT TERMS

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APPROACH

The approach for accomplishing the proposed objectives is model simulation using ROMS (Shchepetkin and McWilliams, 2005) and its comprehensive ocean prediction and analysis system (Moore et al., 2004). Tidal forcing is imposed using available global OTPS model.
ROMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2008; Shchepetkin and McWilliams, 2005). The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgridscale parameterizations (Durski et al., 2004; Warner et al., 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom. Several adjoint-based algorithms exists for 4-Dimensional Variational (4DVar) data assimilation (Di Lorenzo et al., 2007; Powell et al. 2007), ensemble prediction, adaptive sampling, circulation stability (Moore et al., 2004), and sensitivity analysis (Moore et al., 2006).

WORK COMPLETED

Two regional, nested grids have been built: coarse (5 km), and fine (2 km). The initial and lateral boundary conditions are from the 1/12° Global HYCOM with NCODA (provided by Joe Metzger and Harley Hurlburt), atmospheric forcing is from NOGAPS 3-hours, half-degree resolution, and the tidal forcing is from the global OTPS model. Real-time forecasts without data assimilation in the Philippine Archipelago were carried out in support of *Exploratory*, *Joint* and *First IOP* cruises. Each prediction cycle, updated daily, was run for 9 days (4-day hindcast and 5-day forecast). The model was initialized 4 days prior to the forecast cycle starting day to use reanalyzed atmospheric and boundary forcing. Real-time forecasts can be found at http://www.myroms.org/philex.

A tidal harmonic analysis on free-surface and currents was carried out to validate and compare ROMS against OTPS fields. The results show that the barotropic tides are well simulated in ROMS except in the interior of the Philippine Archipelago for the 5km grid. This is improved in 2km grid indicating that finer resolution is needed to resolve the inter-island passages. This analysis was also used to study the structure and generation mechanisms of internal tides. We found that internal tides are generated in the Sulu islands chain and propagate in both directions towards the Sulu Sea to the north and the Celebes Sea to the south.

As a preamble to the data assimilation experiments, optimal perturbations and adjoint sensitivity analysis were performed to identify the validity of the tangent linear approximation, assimilation time windows, and observational operators. Three different adjoint sensitivity metrics have been computed for the Mindoro, Bohol, Surigao, and San Bernardino Straits. They are: transport, velocity anomaly, and temperature anomaly. Results indicate that bathymetry, temperature and velocity are crucial to obtaining a good estimate of transport.

Several observed data from various sources have been assimilated into ROMS including: temperature and salinity data from the *Exploratory Cruise*, gliders and APEX floats, satellite SST, and satellite altimetry. The assimilation improved the model-data fit and model prediction skill. We are currently improving the parameters and algorithms to achieve better convergence and fit. We are developing new algorithms to determine the type of measurements that need to be made, where to observe, and when.

RESULTS

The M2 tidal amplitude and phase from the harmonic analysis is shown in Figure 1 for OTPS (a), ROMS 5km (b) and 2km (c) resolutions.

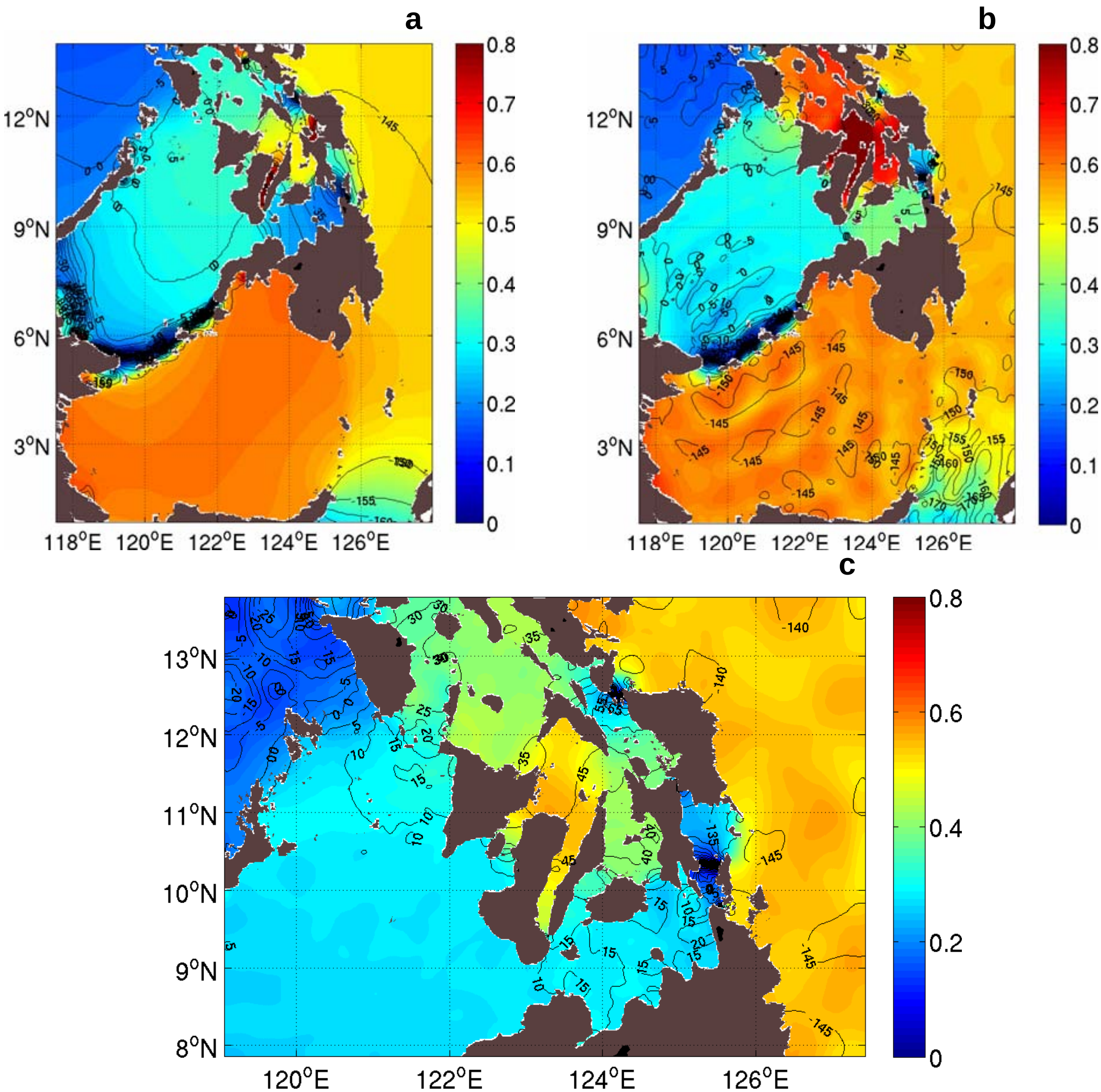

Figure 1. M2 tidal amplitude (m; colors) and phase (degrees; contours) from (a) OTPS at ~10km resolution, (b) ROMS 5km grid resolution, and (c) ROMS 2km grid resolution.

The M2 tide amplitude in the Sulu Sea is around 0.3 m and doubles to almost 0.6 m in the Celebes Sea. The tidal phase lag is around 150 degrees between the two basins. This difference is due to the Sulu islands chain. The same effect is observed over other straits that separate two distinct waters masses. In the interior of the Philippine Archipelago area, the M2 amplitude from 5km ROMS (Fig. 1b) is much higher than OTPS (Fig. 1a). However, the 2km ROMS (Fig. 1c) are closer to the OTPS. A time series of surface elevation (Figure 2) shows good agreement between 2km ROMS (blue curve) and OTPS (red curve) predictions in the Sulu Sea, South China Sea and Pacific Ocean. However, there are some differences in the Bohol Sea (Fig. 2, stations 5, 6 and 7) which is probably due to the different bathymetry smoothing at the strait between ROMS and OTPS.

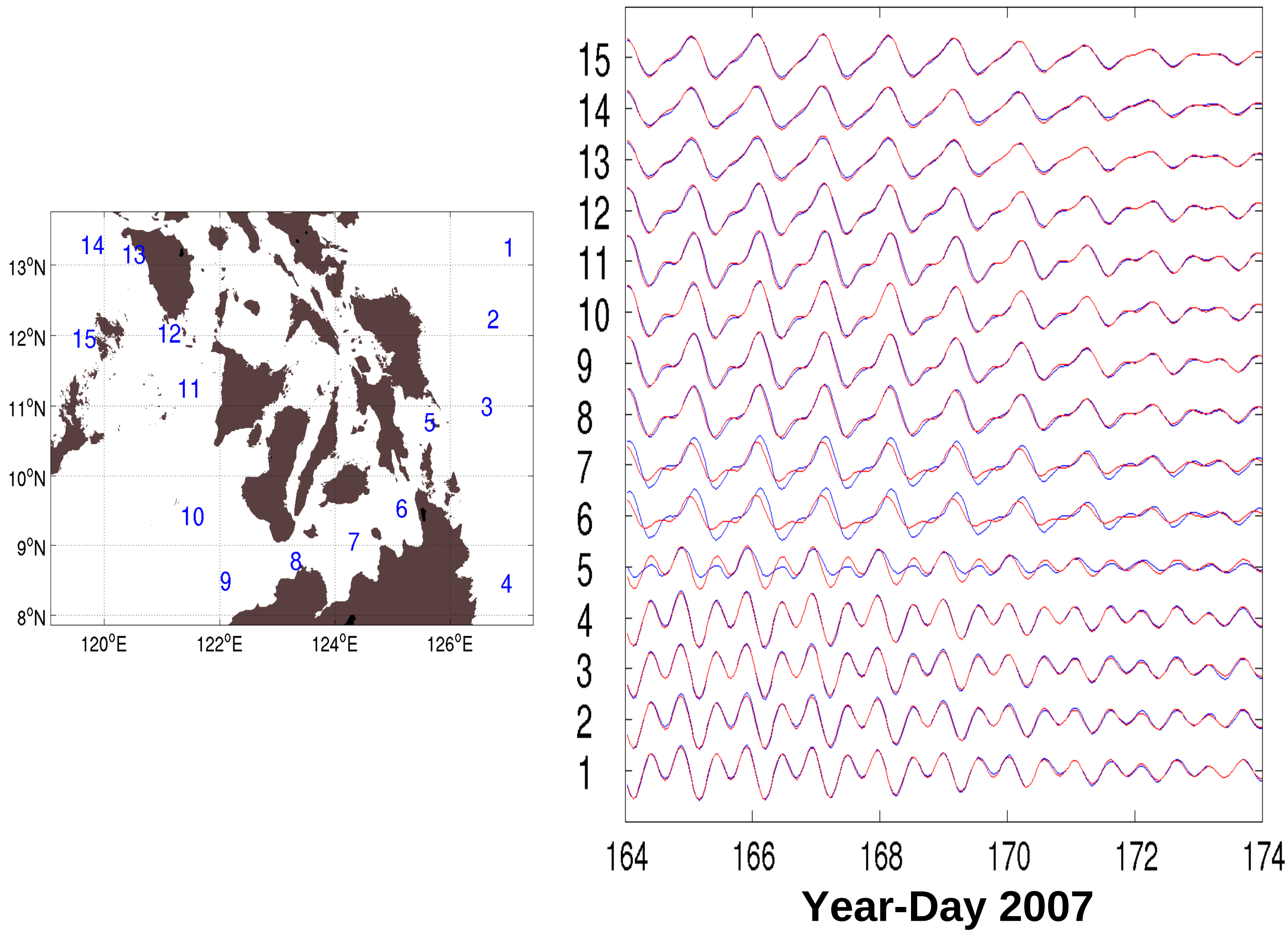

Figure 2. Sea surface height comparison between ROMS (blue; 2km resolution) and OTPS (red; ~10km resolution) models at the locations specified on the left panel map.

The M2 tidal phase shows smaller scale structures in 5km ROMS (Fig. 1b) in the Sulu and Celebes Seas which can be explained by the baroclinic tide's effects on the sea-surface elevation. The phase speed of the baroclinic tide propagation on the sea-surface is around 2.5 m/s, which is closer to that of the first baroclinic mode. The patterns of the M2 amplitude and phase in the Sulu Sea in 2km ROMS

(Fig. 1c) are smoother than in 5km ROMS (Fig. 1b). This is because the Sulu islands chain is not included in the 2km grid excluding the generation source of internal waves and baroclinic tides. Notice that the southern boundary for the 2km grid is around 8° N and the Sulu island chain is centered around 6° N. The Sulu islands chain plays an important role in the generation of baroclinic tides.

Figures 3 and 4 show the results of data assimilation runs using CTD data from ships, gliders, APEX floats, altimetry (AVISO), and SST composites from Micro-Wave and IR satellites. This was assimilated into 5km ROMS. To better constrain the model in areas where no data is available, the climatological data from Levitus 2001 is also assimilated. Much smaller observation errors are assigned for *in situ* data than for climatological data. This allows the assimilation system to give more weight to *in situ* than climatological data. The impact of data assimilation on salinity and temperature is examined in Figures 3 and 4, respectively along the *Exploratory Cruise* track (Fig. 3d and 4d). The control run without data assimilation is shown in Figures 3b and 4b, while the results with data assimilation are shown in Figures 3c and 4c. Comparisons show that assimilation is able to remove excessive salt (Fig. 3f) in the Sulu and Bohol Seas and Leyte Gulf (Stations 1-25, 28-80). Analysis of stations 26 and 27, in the Pacific Ocean, also shows that assimilation removed excessive salt from the surface, and created a more pronounced subsurface salty layer. Improvement is also noticeable in the Sibuyan Sea (Stations 90-100). Overall, the rms error in salinity is decreased from 0.17 to 0.09 by assimilation. Similarly, the rms error in temperature is decreased from 2.1 to 1.3 Celsius.

IMPACT/APPLICATIONS

This project will advance our scientific understanding of the generation dynamics and predictability of meso- and sub-mesoscale eddies near straits.

TRANSITIONS

None.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (Arango) closely collaborates with A. Moore and B. Powell (Intra-Americas Sea trials, http://www.myroms.org/ias) at University of California, Santa Cruz, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

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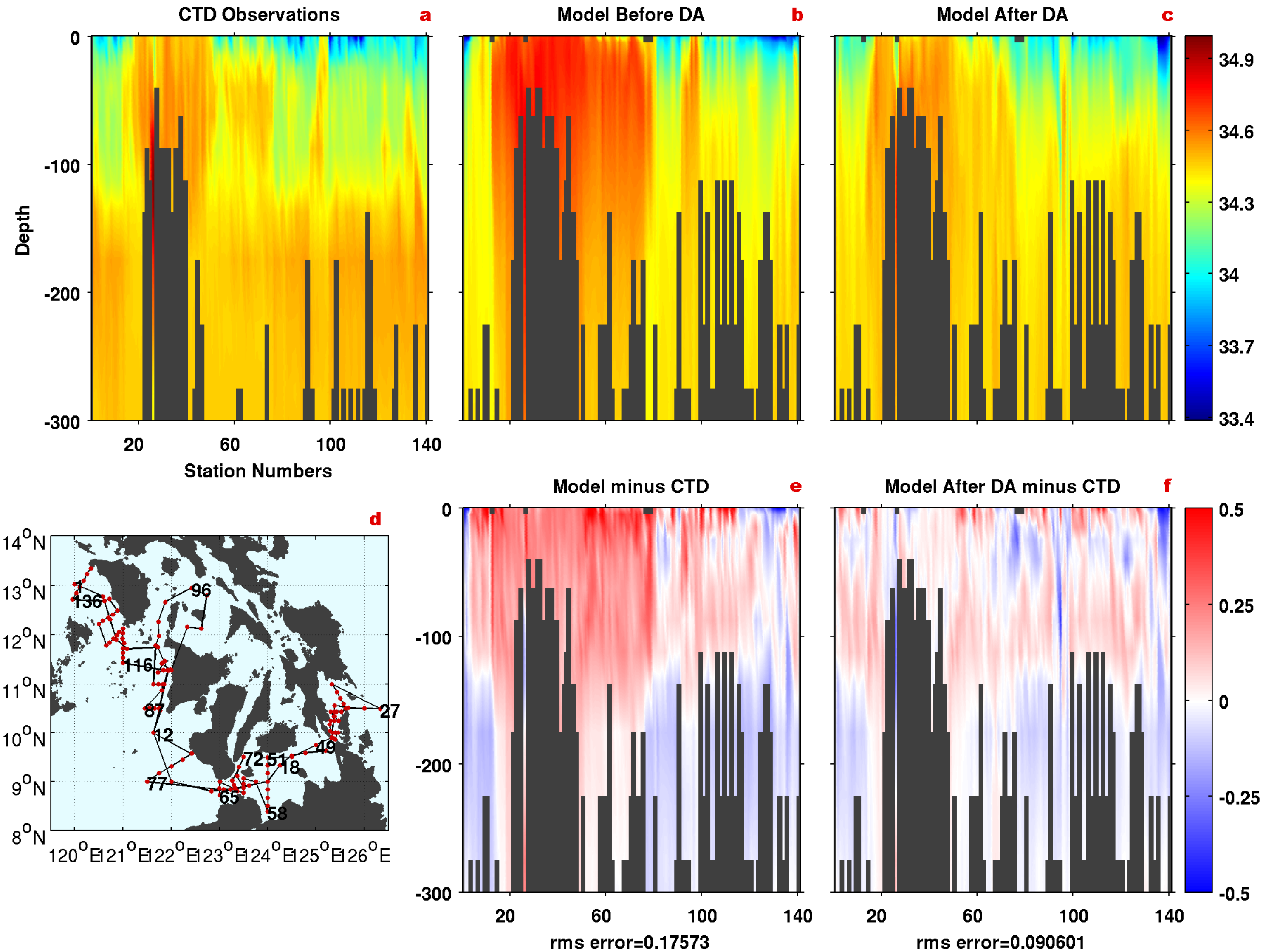

Figure 3. Salinity comparison between observations and model at CTD locations (d): Observed salinity (a), model salinity without (b) and with (c) data assimilation, salinity difference between observations and model without (e) and with (f) data assimilation.

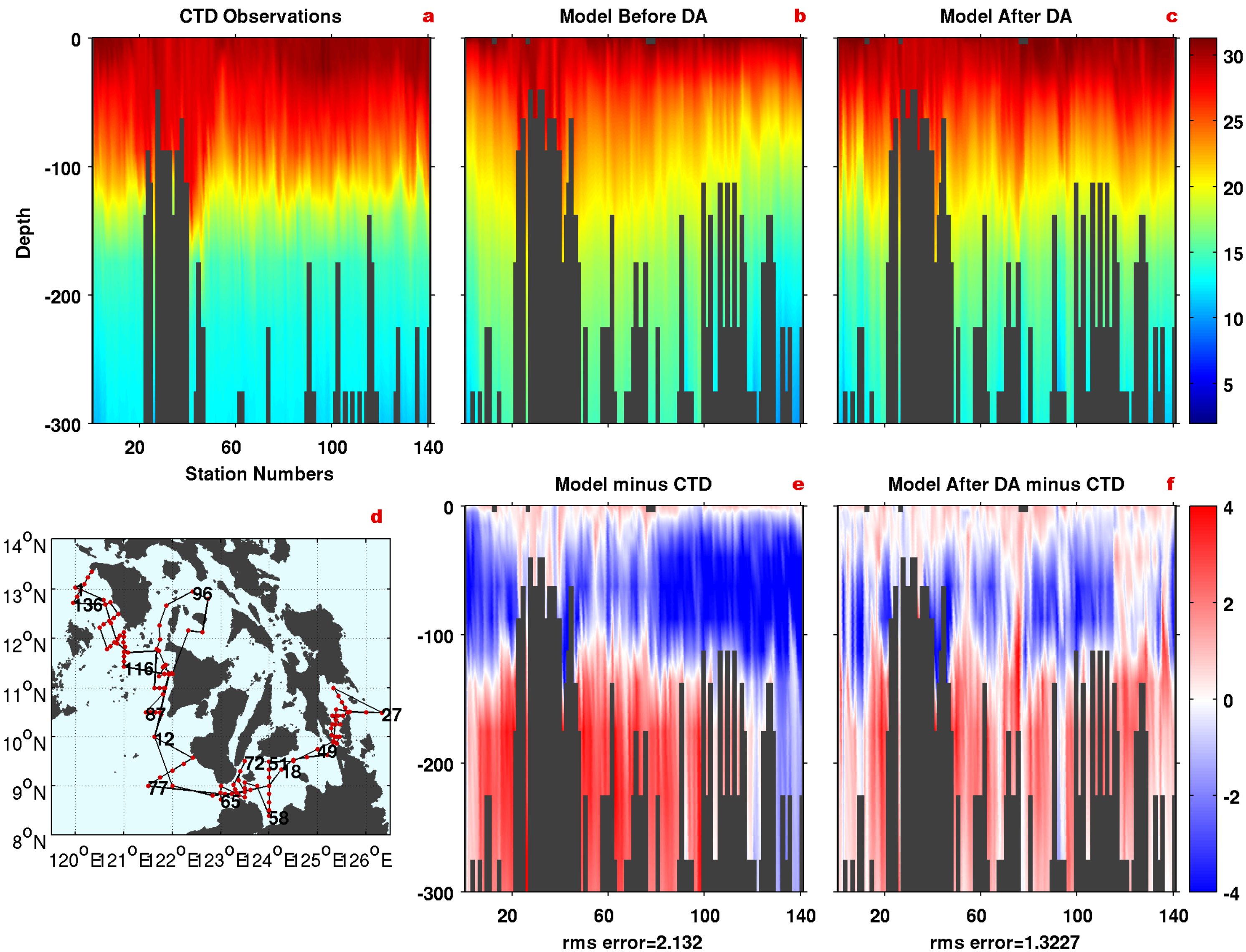

Figure 4. Temperature comparison between observations and model at CTD locations (d): Observed temperature (a), model temperature without (b) and with (c) data assimilation, temperature difference between observations and model without (e) and with (f) data assimilation

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